# Advances in Seismic Imaging and Modeling for the Petroleum Industry

*L. House (house@lanl.gov), M. Fehler, L. Huang, and P. Roberts, with S. Hildebrand, D. Alde, and C. Aprea (EES-11)*

The oil and gas industry has relied on seismic reflection methods as its primary exploration tool for more than 50 years. During that time, the quantity of data being collected and the amount of time needed to analyze these data has increased dramatically, and the quality of the data has improved remarkably as well. The increasing use of three-dimensional (3-D) seismic methods is an example of this. Using these methods, we have gained extraordinary new insights into the structure, stratigraphy, and rock properties of the subsurface, but a single 3-D survey may generate hundreds of gigabytes of data, which creates huge demands on the computing resources needed to process it properly. We recently developed a suite of four new seismic imaging methods, termed dual-domain methods (for space and wave-number domains), that attempt to address these issues.

To process seismic reflection data fully requires many steps, beginning with initial trace editing and ending with “imaging,” or migration. Imaging is the most time-consuming step in the processing sequence, and for areas of complicated geological structure, it is the single most important step in the processing sequence. Imaging of a full 3-D survey may take many months, mainly because of the computing time required. Industry has recently explored for oil and gas in geological settings that are extremely difficult to image properly, such as subsalt areas, where 3-D seismic imaging is crucial. Subsalt imaging is difficult because of the large seismic velocity contrast between the salt body and the surrounding sediments. In addition, the generally irregular surfaces of salt bodies bend, reflect, and convert seismic waves in directions and ways that are almost unpredictable.

Unraveling the extreme effects that salt bodies can have on seismic waves as they go downward into the Earth and then return to the surface is the essential work done by the imaging step. The reliability of the resulting image depends on the quality of the seismic data and the reliability of the velocity model of the subsurface that is used. Unfortunately, defining the velocity model usually requires the results of the imaging. Thus, several iterations of improving the velocity model and running the imaging may be needed to get a reliable final image. Since a single imaging step may require months of computing to carry out, industry has devoted considerable resources to finding ways to speed up the imaging step.

All practical imaging methods use carefully chosen approximations to the exact imaging methods so they can run as fast as possible. Unfortunately, each approximation may also introduce inaccuracies into the resulting image. An important part of imaging research is to understand and evaluate the potential negative effects of the various approximations on the image. Test data sets, for which the proper image is known, are very important for understanding the effects of the imaging approximations.

The Kirchhoff imaging method is the fastest practical imaging method but involves the largest number of approximations. In spite of this limitation, it is the method most commonly used by the industry. Other imaging methods have been developed that are more reliable than Kirchhoff, but they can be so computing intensive that they are not practical for routine use. Our objective is to develop new imaging methods that fulfill two objectives: first, to produce more reliable images than the Kirchhoff method; and second, to keep the computing time required short enough to be practical.

In addition to developing higher-quality imaging methods, a crucial part of imaging research is to use seismic (forward) modeling to validate imaging methods and the velocity models they depend on. Researchers produce synthetic seismic data from specified structures, and the resulting synthetic data are then used to test and validate the imaging.

As with imaging, seismic modeling is an extremely computing-intensive procedure. Nevertheless, reliable, fast, and versatile seismic modeling is an essential part of testing and verifying imaging results and interpretations. Seismic modeling is also an increasingly important part of other aspects of seismic processing. With the increased use of three- and four-component data collection, the ability to carry out full 3-D elastic model calculations is increasingly important. Even with the fastest computers, 3-D elastic modeling is slow, and new, faster methods are needed to keep pace with the demands of the industry.

## New Seismic Imaging Methods

Four new seismic imaging methods described below use slightly different approximations to the wave equation and are best suited to specific types of subsurface velocity fields. We named each of the four methods for the approximation they make to solve the wave equation: (1) Born, (2) Rytov, (3) quasi-Born, and (4) globally optimized Fourier finite-difference. The Born method assumes that lateral velocity perturbations are small in magnitude but may be abrupt in space. The Rytov method assumes that velocity perturbations are smooth but may be large in magnitude. The quasi-Born method adds a factor to the Born integral that improves the accuracy and the computational stability of the Born method. The increased stability allows use of a coarser computational grid, so fewer computing steps are needed, thus, the imaging is faster. Finally, the globally optimized Fourier finite-difference method is a hybrid method in which lateral derivatives of the wave field are computed in two parts—one is exact and the other has an approximation with relatively small error.

All four methods involve a recursive extrapolation of the recorded wave field downward into the Earth. The extrapolation at each depth step operates on the result of the previous depth step. The depth extrapolation is followed by an imaging step, which produces the image of the subsurface at the level of the current depth step. These imaging methods are almost as accurate as methods based on the full wave equation but require much less computer memory and are as much as 100 times faster.

Using these new imaging methods, we have successfully produced high-quality images of structures beneath salt bodies, which is an extremely challenging imaging situation. Figure 1 shows an example structure (top) and the image (bottom). The image was obtained with the globally optimized Fourier finite-difference method. In this case, the characteristics of the image are known exactly because it was generated from a synthetic data set. This figure shows what is arguably one of the best images ever obtained from this test data set, and many researchers have tested their imaging methods using it.

## Improvements to the Kirchhoff Imaging Method

The Kirchhoff imaging method has been the imaging workhorse for the oil and gas industry for many years. It is much faster than other imaging methods, although it involves assumptions and approximations that often produce poorer images than those of other, slower methods. With the need to minimize time and cost, however, industry often finds that the slower methods are just not practical. Yet the images produced by conventional Kirchhoff migration are inadequate in complex geological structures. An essential part of the Kirchhoff method is computing the travel times of seismic waves along ray paths between every source and receiver. Conventional Kirchhoff imaging methods use fast, but simple, methods of computing the travel times. These methods provide excellent results in simple structures but rather poor results in more complicated structures, such as subsalt, where ray paths may be bent severely and cross other ray paths. Another major problem with

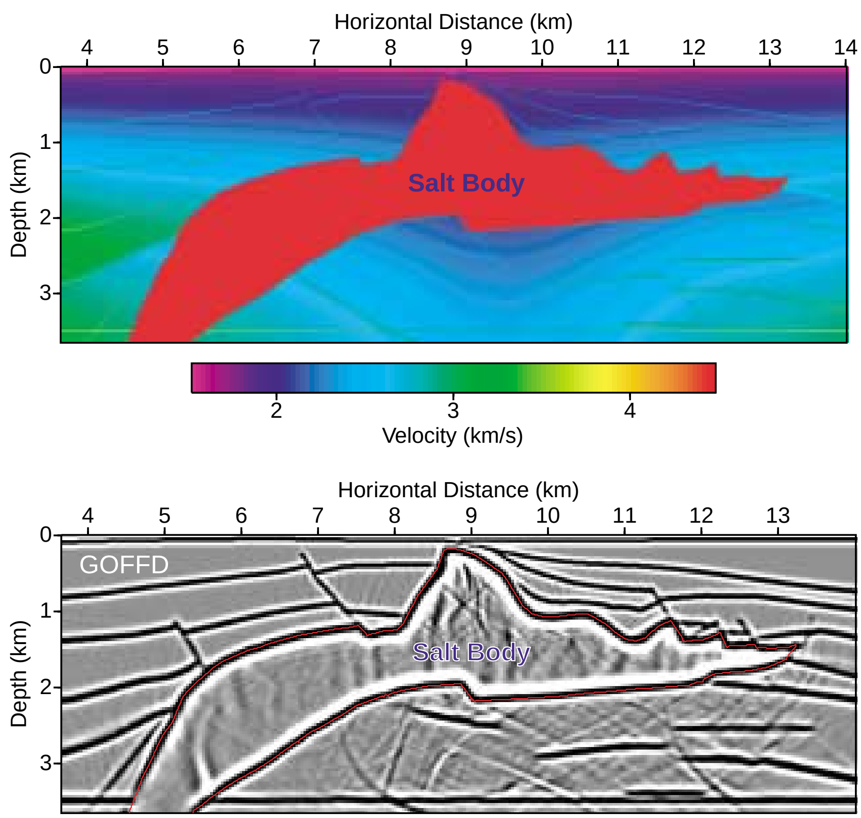


**Figure 1. Image of a Salt Structure.**
The top diagram is a 2-D vertical slice from a model of a hypothetical salt body. Note the extreme contrast in seismic velocity between the salt body and the surrounding sediments. Synthetic seismic data were computed from this model for testing imaging methods. The bottom panel is an image from a 2-D prestack migration of the synthetic data. This image was produced by the globally optimized Fourier finite-difference method and is an excellent image from this complicated structure.

conventional Kirchhoff imaging methods is that they exploit only first-arriving seismic waves. These waves may have followed such complicated ray paths that they only have small amplitudes and make minor contributions to the image.

To improve the imaging ability of Kirchhoff imaging methods and still retain their speed advantage, we have developed two techniques: wave-front construction and multiple-arrival Kirchhoff imaging. These techniques provide more reliable travel times and allow the use of multiple arrivals in the imaging. Although adding these techniques slows down the Kirchhoff imaging, it is still faster than other, more exact, imaging methods.

The new technique of wave-front construction provides a more robust method for computing travel times. The basic concept is that a wave front, composed of many individual seismic rays, is propagated through the velocity model, and travel times are computed from the advance of the entire wave front rather than from individual ray paths.

The propagation of the wave front is stable, even in velocity structures in which individual ray paths may shift drastically with only slight changes in their starting or ending positions. With more reliable travel times, the wave-front construction method produces better images from the Kirchhoff imaging method, particularly in complicated structures such as those beneath salt.

The second new technique addresses the problem of first arrivals being so small that they make little contribution to the image. In this situation, improving the image requires using the energy in several seismic arrivals. Multiple-arrival Kirchhoff imaging promises to produce better, more reliable, and more interpretable images from complicated structures. On the other hand, computing multiple travel times adds to the computational burden of Kirchhoff imaging. This method should still be fast enough so that it can be a practical imaging method, especially for getting initial images.

## New Seismic Modeling Methods

At the opposite end of the spectrum of seismic reflection methods from imaging are seismic modeling methods. Using seismic modeling, one takes a known geological structure and computes the synthetic seismic response that would be recorded at specified sources and receivers. These forward methods are usually more precise than imaging methods and are crucial for testing imaging methods.

We devised two new seismic modeling methods that adapt the lattice-Boltzman microscale approach from fluid-flow modeling to simulate the physical processes of seismic wave propagation. These fully discrete methods can simulate all wave phenomena resulting from the complexity of a medium, using essentially no approximations. The methods simulate wave propagation through microscopic physical processes of the quasi particles that carry the wave field. These processes include transport between lattice nodes, reflection/transmission, and collisions.

The two new methods differ slightly in the way the quasi particles interact. They can accurately simulate wave propagation in media with sharp interfaces, strong contrasts in velocities, large topography, and viscosity/attenuation. In contrast, conventional finite-difference wave modeling methods require that the medium have only smooth changes in properties, which is often an unrealistically simplified view of the Earth. The lattice-Boltzman seismic modeling methods are also well suited for taking advantage of the currently available parallel computing systems. An example snapshot of a synthetic wavefield from one of the lattice-Boltzman modeling methods is shown in Figure 2. This figure illustrates the ability of the methods to model the topography at the surface of the model accurately and easily, which is difficult for finite-difference wave-equation modeling methods to do. The figure depicts a homogeneous velocity model (green background) with surface topography (the green and purple interface near the top of the figure). The calculated waves from a source at the middle of the figure are shown in red and purple. The circular wave front has reached the bottom of the model, from which there was no reflection because of the absorbing boundary condition on it. The wave front has nearly reached the sides of the models. The most interesting part of the figure is the interaction between the model waves and the topography, which has produced a complicated series of reflected waves and numerous multiples.

## Project Collaborators

In addition to developing the new imaging and modeling methods discussed above, we are collaborating with researchers at Stanford University, the University of California at Santa Cruz, and the Lawrence Livermore National Laboratory to develop and test other methods for imaging and modeling. One new imaging method exploits the regular geometry of marine seismic data to make it faster. The method should be able to speed up wave-equation-based imaging by a factor of 10 or more yet still retain the inherently better-resulting image of wave-equation-based methods. The modeling method is a fully elastic 3-D method that effectively uses parallel computing to help speed up the calculations. It has been used and validated by many oil and gas and service companies. The capabilities of the method are still being enhanced and improved.

In addition to the collaborators at Stanford University and the Lawrence Livermore National Laboratory, this work is being done as collaborations with companies from the oil and gas industry. The projects have more than two dozen collaborating companies. These collaborators provide guidance, insights, test data sets, new algorithms, and many hours of their own time to each project. The collaborations have been essential to the success of the research projects. The industry collaborations, which continued even through the most recent down-cycle in the industry, demonstrate the high level of interest by industry in this research and underscore the importance of the substantial contributions the projects have made in seismic imaging and modeling.

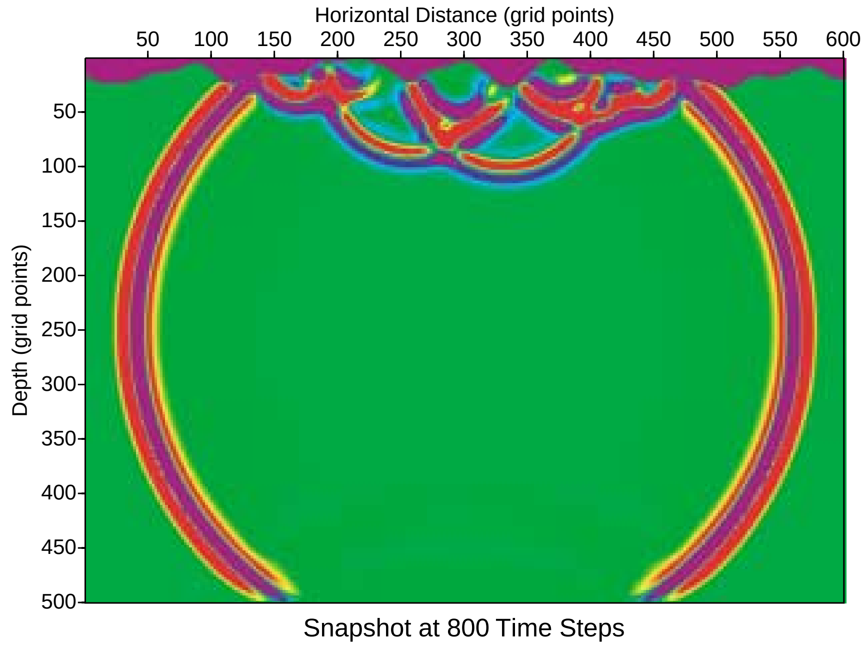


**Figure 2. Lattice-Boltzmann Modeling.**
The figure is a 2-D slice of a wave-propagation simulation in a homogeneous velocity medium (indicated by the green background color) with large surface topography. The surface topography is the irregular interface between the blue and green materials. This is a situation that is difficult to model properly using conventional finite-difference methods. It was successfully modeled with the lattice-Boltzmann modeling method.

## Conclusions

We have developed several new methods for imaging seismic reflection data that have significant advantages compared to conventional imaging methods. These advantages include substantially reduced computing requirements with little or no degradation of the final image.

We have also developed new methods for more accurately computing synthetic seismic data. These can also be used to compute synthetic data from subsurface models that are beyond the abilities of conventional modeling methods. Accurate imaging and modeling methods are crucial for making maximum use of large 3-D seismic data sets. ■

## Further Reading

Fehler M., H. Sato, L.-J. Huang. 2000. Envelope broadening of outgoing waves in 2D random media: A comparison between the Markov approximation and numerical simulations. *Bulletin of the Seismological Society of America* **90**: 914–928.

Fehler, M., L.-J. Huang, D. Alde, S. Hildebrand, and C. Burch. 1998. Comparison of images obtained from a 2D Gulf of Mexico subsalt dataset using different migration approaches. *Expanded Abstracts, Society of Exploration Geophysics, 1998 Annual Meeting*.

Huang L.-J., P. Mora, M. C. Fehler. 2000. Absorbing boundary and free-surface conditions in the phononic lattice solid by interpolation. *Geophysical Journal International* **140**: 147–157.

Huang L.-J., and M. C. Fehler. 2000. Quasi-Born Fourier migration, *Geophysical Journal International* **140**: 521–534.

Huang, L.-J., M. C. Fehler, P. M. Roberts, and C. C. Burch. 1999. Extended local Rytov Fourier migration method, *Geophysics* **64**: 1535–1545.

Huang, L.-J., M. C. Fehler, and R.-S. Wu. 1999. Extended local Born Fourier migration method. *Geophysics* **64**: 1524–1534.

Huang L.-J., and M. C. Fehler. 1998. Accuracy analysis of the split-step Fourier propagator: Implications for seismic modeling and migration. *Bulletin of the Seismological Society of America* **88**: 18–29.

Roberts, P., L.-J. Huang, C. Burch, M. Fehler, and S. Hildebrand. 1997. Prestack depth migration for complex 2D structure using phase-screen propagators. *Expanded Abstracts, Society of Exploration Geophysics, 1997 Annual Meeting*, p. 1282.